TRANSMISSION OF URGENT MESSAGES
IN TELEMETRY SYSTEM

Cross-Reference to Related Application

5   This application claims the benefit of U.S. provisional application Ser. No. 60/156,827, filed September 30, 1999, and entitled "Power-up Synchronization in Frequency Hopping System For Intermittent Transmission", which is incorporated by reference.

Field of the Invention

     The present invention relates to telemetry in general, and, more particularly, to a system in which 10   a plurality of transmitters wirelessly transmit transmissions for processing by one or more receivers.

Background of the Invention

     Some wireless telemetry systems (*e.g.*, burglar alarms, fire alarms, power utility meters, leak detectors, environmental monitoring, temperature control, *etc.*) comprise many transmitters that periodically or sporadically transmit messages to one or more receivers. In these systems, each 15   transmitter is located at a different place and transmits messages that indicate the status of sensors associated with the transmitter. A centrally located receiver receives messages from each transmitter.

     Normally, the transmitters transmit messages that are as short as feasible and with the interval between the transmissions as long as feasible. This is advantageous for two reasons. First, it minimizes the average current drain in the transmitters, which are typically battery operated. Second, short and 20   infrequent transmissions lower the probability that data is lost as a result of collisions that occur when two or more transmitters transmit at the same time.

     However, if an urgency is detected by the sensor associated with the transmitter, the transmitter transmits immediately in order to notify the receiver of the urgency as soon as possible.

     Typically, a telemetry system transmits at a single frequency, and thus is susceptible to 25   narrowband interference and signal loss due to a phenomena known as "multipath fading." As a consequence, the reliability of such systems is compromised or, conversely, the transmitted power has to be increased to overcome the fading, which results in larger power drain and shorter battery life. Furthermore, there usually are regulatory limits that restrict such transmitter power and thus limit the possible compensation for multipath fading by merely increasing the transmission power.

Because the multipath effect is highly sensitive to the frequency of the transmitted carrier, a system using multiple frequencies (*e.g.*, a frequency hopping spread spectrum system, *etc.*) has the potential to eliminate these drawbacks. However, frequency hopping systems require a long acquisition time and are typically used in two way communication applications in which all the devices can be

5   synchronized by continuously synchronizing with one master device or with each other using a variety of synchronization methods suitable for such case.

In other cases, to ease the synchronization problem, there are employed receivers that can simultaneously receive signals at many frequencies by making the receiver broadband or by using several receivers at the same time. Generally, these receivers suffer from performance degradation or high cost

10   or both which makes them undesirable for low cost applications that require high reliability such as security systems.

One serious problem that must be addressed in battery operated systems concerns battery life, and, therefore, it is advantageous if a telemetry system could be devised that shortened a transmitted messages preamble. A short preamble, however, makes it difficult for the receiver and the transmitter to

15   become and stay synchronized. This problem is exacerbated in some systems, such as security alarms, that require some messages to be conveyed to the system immediately without waiting for the scheduled transmission time.

Summary of the Invention

Some embodiments of the present invention comprise a frequency hopping receiver that acquires

20   and maintains synchronization with a plurality of transmitters, which enables the transmitters to omit the transmission of long preambles. This is advantageous because it lowers the average current drain in the transmitters and, consequently, lengthens their battery life. Furthermore, some embodiments of the present invention are advantageous in that they provide improved reliability in the presence of multipath fading, interference and jamming. And still furthermore, some embodiments of the present invention are

25   capable of eliminating the effect of persistent collisions that occur when two or more transmitters transmit at the same time in the same channel for a prolonged period.

The illustrative embodiment of the present invention is a frequency-hopping wireless telemetry system comprising: (1) one or more receivers, and (2) one or more transmitters, each of which receive input from one or more sensors. The transmitters intermittently transmit very short messages indicative

30   of status of the sensors associated with the transmitters. Each transmitter includes a time interval generator to establish the time interval between successive transmissions, a frequency synthesizer-modulator to generate a modulated radio frequency carrier signal wherein the frequency of

the carrier changes in response to programming the synthesizer by digital data, a reference frequency oscillator to provide a frequency reference from which the synthesizer derives carrier frequencies and, advantageously, from which the time interval generator derives its timing, and a transmitter control logic activated in response to pulses from the time interval generator or a sensor signal indicating an abnormal

5   condition. When activated, the transmitter control logic activates and programs the synthesizer so that the transmitter carrier frequency is changed according to a frequency hopping algorithm, provides digital data indicative of the sensor status and advantageously battery status, and modulates the carrier with the provided data. The receiver includes a frequency selective radio receiver circuit, programmable by digital data, to receive and demodulate a transmitted carrier when the frequency of the receiver circuit is

10   programmed according to the frequency of the carrier, and a receiver control logic means to process demodulated data, to provide system interface responsive to the received messages, and to program the frequency of the frequency selective receiver circuit. The control logic includes a receiver timer to measure the elapsing time, and a plurality of memory registers to hold digital data indicative of (a) the time of the next transmission occurrence for each transmitter and (b) the frequency of the next

15   transmission occurrence for each transmitter. In operation, the control logic sequentially compares the data content of the time registers with the data content of the timer and if the transmission is due from a transmitter, the control logic programs the frequency selective radio receiver circuit according to the data content in the frequency register associated with said transmitter, attempts to decode the demodulated signal, modifies the content of the time register by a number representative of the time interval between

20   the successive transmissions for said transmitter and modifies the content of the frequency register according to a predetermined algorithm for said transmitter.

In accordance with the illustrative embodiment of the present invention there is provided a method of transmission in the system so as to improve reliability of the system in the presence of multipath fading and interference, the method is based on varying the transmission frequency for each

25   transmitted message and varying the time between consecutive messages. The frequency variations provide frequency diversity and are effective against multipath fading as well as single of multiple narrowband interference. The time variations are effective against periodic impulse interference. In combination, the frequency and time variations provide immunity for a wide variety of signal impairments and interference including multipath fading, wide and narrowband interference, impulse

30   noise and deliberate jamming.

In accordance with the illustrative embodiment of the present invention there is provided a method of minimizing the effect of collisions, the method is based on selecting the transmission

frequencies in sequences that are different for each transmitter, wherein transmitter frequency sequence depends on the transmitter ID number or other number derived or associated with the transmitter ID. In addition, in the illustrative embodiment, the transmitter ID number or other number derived or associated with the transmitter number is included in the transmitted message, so that, upon reception of a single

5   message from a transmitter, the receiver can determine what is the next frequency for this transmitter, and thus achieve synchronization with this transmitter.

In accordance with the illustrative embodiment of the present invention there is provided another method of minimizing the effect of collisions that can be used alone or in conjunction with the third aspect of this invention, the method comprising randomizing the time interval between transmissions

10   individually for each transmitter and a receiver compensating for the time interval changes.

In accordance with the illustrative embodiment of the present invention there is provided a simple method to generate a very large number of frequency-time hopping sequences. The method produces sequences that are orthogonal, thus eliminates possibility of persistent collisions even when large number of transmitters are used. In addition, the method requires identical circuit in each transmitter and the

15   actual sequence that is produced is selected by the transmitter ID or other number associated with the transmitter ID, thus making it convenient for manufacturing. Also, the method enables to produce a very large number of frequency-time sequences based on a single short PN generator whose state can be instantly recovered by a receiver based on just one received transmission, thus aiding the receiver in obtaining synchronization with a transmitter whose ID is known. At the same time, because of a very

20   large number of possible sequences that can be generated, it is difficult to obtain synchronization if the transmitter ID is not known, which makes the system immune to interception and jamming.

In accordance with the illustrative embodiment of the present invention, there is provided a method that enables such a system to convey the information about an abnormal sensor condition as soon as the condition occurs regardless of the transmission period of the associated transmitter. The method is

25   based on transmitting urgent messages on one of a plurality of transmission opportunities that allow the receiver to tune to the right frequency at the right time to check if there is any transmission pending form a transmitter. The urgent messages are, advantageously, synchronized to the routine messages, in effect, making the routine transmission an aid for the receiver in synchronization and tracking of the transmission opportunities.

30   In accordance with the illustrative embodiment of the present invention, there is provided a method that enables such a receiver to obtain a rapid synchronization with a transmitter after a transmitter is powered-up. The method is based on rapidly transmitting, at transmission opportunities, a sequence of

many synchronization transmissions that carry information about the time and the frequency of a future routine transmission.

Brief Description of the Drawings

5   FIG. 1 is a block diagram of a transmitter according to a advantageous embodiment of the present invention.

FIG. 2 is a block diagram of a receiver according to a advantageous embodiment of the present invention.

FIG. 3 is a block diagram of an example of illustrative embodiment of a sequence generator used to

10   determine the individual frequency sequences.

FIG. 4 is a block diagram of an example of a illustrative embodiment of a sequence generator used to determine the individual frequency-time sequences.

FIG. 5 is a block diagram depicting the frequency hopping system including many transmitters and a receiver.

15   FIG. 6a is a block diagram depicting an example of routine transmissions.

FIG. 6b is a block diagram depicting an example of routine transmissions and transmission opportunities.

FIG. 6c is a block diagram depicting an example of transmission of urgent transmissions.

FIG. 6d is a block diagram depicting another example of transmission of urgent transmissions.

20   FIG. 6e is a block diagram depicting an example of relating routine transmissions with transmission opportunities based on a decimation of a basic sequence.

FIG. 6f is a block diagram depicting an example of relating routine transmissions with transmission opportunities based on two different basic sequences.

FIG. 7a is a block diagram depicting a synchronization sequence and routine transmissions for

25   one transmitter.

FIG. 7b is a block diagram depicting a synchronization sequence and routine transmissions for two transmitters.

Detailed Description

Referring to FIG. 5, the illustrative embodiment of the present invention depicts telemetry system

30   comprising: receiver 401 and a plurality of transmitters 402, 403, 404 and 405. Receiver 401 is a wireless

reciever as described in detail below that includes a system interface **410** through which the receiver can be connected to interface equipment (*e.g.*, a controller, a computer, *etc.*).

Each transmitter includes an interface or a sensor or an operation to be monitored, and each transmitter intermittently transmits short messages to the receiver that indicate, among other things, the status of the associated sensor(s) or device(s) or operation(s). The transmitters are not connected to each other and do not receive messages back from the receiver. *I.e.* a transmitter does not have the capability to receive signaling, timing or data from other transmitters or from the receiver. Furthermore, a transmitter transmit messages when it needs to without any regard to whether the other transmitters are transmitting and without regard to the receiver.

Referring to FIG. **1**, the illustrative embodiment of a transmitter comprises a reference frequency crystal oscillator **6** to produce a stable frequency on line **26**, a time interval generator **2** establishing a time base to produce pulses on line **28** activating the transmitter, a frequency synthesizer-modulator **4** to produce a radio frequency carrier modulated by modulation data fed to the synthesizer via line **24** wherein the frequency of the carrier is programmed to a desired value via plurality of lines **14**, transmitter control logic **8** to activate and program the synthesizer-modulator **4** via plurality of lines **14** when the logic is activated by a pulse from the time interval generator or by an abnormal signal indication on a sensor signal input line **18**, an amplifier **10** to amplify the radio carrier provided by the synthesizer when the amplifier is activated by the control logic **8** via line **16**, and an antenna **12** to radiate the power delivered by the amplifier. The control logic **8** includes a frequency and time data memory register **20** to hold information used to determine the time and the frequency of next transmission, and a sensor interface circuit **22** to accept the sensor signal and detect an abnormal signal condition, and to convert the sensor signal to a digital format suitable for transmission. The transmitter logic also includes a storage means **30** to store a transmitter ID number to differentiate this transmitter from other transmitters. The transmitter control logic, in some systems, can be realized based on microprocessor, in some other systems, a specialized application specific integrated circuit – ASIC component may be used.

In operation, during the time between transmissions, the transmitter is in a standby mode in which the amplifier **10** and synthesizer-modulator **4** are not active and, advantageously, the control signals turn off the power from these circuits in order to minimize the standby current of the transmitter. The transmitter control logic **8** is in a standby mode in which the most of the circuits are inactive and some or most of the circuitry can be powered down with the exception of the circuits supporting critical functions; (a) the sensor interface circuit **22** that detects an abnormal signal condition and produces a binary signal that is logically combined with the signal **28** produced by the time interval generator so that when either a pulse or abnormal

condition occurs the rest of the transmit logic circuitry is activated or powered up, (b) the frequency and time data memory **20** that has to retain the data during the period between transmission and consequently either it has to be a nonvolatile type or it has to be powered up during the period between transmissions. Upon activation, the control logic **8** determines the activation source by reading signals **28** and **18**.

5   When the logic **8** is activated by a pulse **28** from the time interval generator the following sequence of events occurs. First, the logic reads the frequency data memory and produces a data packet that includes the sensor status, the transmitter ID number and other data such as battery status. Then, the logic activates and programs the synthesizer-modulator **4**, activates the amplifier **10** and sends the packet to the modulator via line **24**. After completion of each transmission, the transmitter logic sets the transmitter in the standby

10   mode until activated again by a pulse on line **28** or a sensor abnormal condition indicated on line **18**.

In the advantageous embodiment the transmission of a packet can be repeated a predetermined number of times at separate frequencies, wherein the number of repetitions is chosen according to application needs and, wherein the frequencies are determined by the transmitter logic according to an algorithm described later in details. This way, it is possible for the receiver to receive some repeated

15   packets even if the other packets are lost due to frequency selective fading caused by multipath or due to interference. Similarly, a single packet can be split into several pieces and each piece transmitted at a separate frequency. In yet another embodiment, it may be advantageous to use more than one carrier at the same time to improve reliability, however this would require a more complex transmitter.

When a sensor abnormal condition occurs, the sensor interface circuit **22** produces an active level of

20   the signal indicative of the sensor abnormal level which activates the transmitter via a combinatorial logic circuit that combines the sensor abnormal level signal with the pulses from the time interval generator. When activated this way, the transmitter control logic **8** produces a data packet that includes the sensor status, then the logic activates and programs the synthesizer-modulator **4**, activates the amplifier **10**, and sends the alarm packet to the synthesizer-modulator.

25   In the advantageous embodiment, the transmission of such alarm packet is repeated a number of times according to the methods described later in details.

After the transmission sequence is completed, the control logic disables the signal indicative of the sensor abnormal status so that an abnormal sensor status can not activate the control logic. Then, the control logic puts the transmitter in the standby mode until activated by a pulse from the time interval

30   generator. When subsequently activated, the transmitter control logic performs the usual transmission sequence but the data packets include information that the sensor condition is abnormal if the condition

persists. When the abnormal condition subsides, the signal indicative of an abnormal status is enabled so that a subsequent occurrence of an abnormal condition can activate the logic and trigger a new alarm transmission sequence. Thus, normal operation is restored.

5   Although FIG. 1 shows a specific illustrative embodiment, it is apparent that various modifications may be realized such as including more than one sensor, placing different ID in each sensor, or even placing the entire control logic in a sensor, or combining transmitter and sensor, *etc.*

        In the advantageous embodiment, the sequence in which the frequencies are used is different for different transmitters. The following is the description how this is accomplished in the advantageous embodiment. Each transmitter includes a pseudo random sequence generator or pseudo noise – PN

10   generator, wherein a pseudo random sequence generator is based on a linear feedback shift register, and wherein some outputs of the shift register are fed back to an EX-OR (Exclusive OR) gate whose output is connected to the register input. For a certain combination of the outputs that are fed to the EX-OR gate, the shift register can produce a sequence that has 2^N-1 bits, wherein N is the length of the shift register. Such a sequence is called a maximum length sequence. Alternatively, if all the outputs of the shift register are

15   taken at a time, then a pseudo random sequence of 2^N-1 numbers is created, wherein all the numbers have N digits and each number differs from all the other numbers in the sequence; the numbers range from 1 to 2^N-1. For example, a generator based on a 3-bit shift register produces a sequence consisting of 7 3-bit numbers. The numbers range from 1 to 7. Such PN generators are well known to the skilled in the art.

        Referring to FIG. **3**, the pseudo random sequence generator **203** consists of a shift register **205** and

20   EX-OR gate **204**. The shift register **205** is composed of three stages **221**, **222**, and **223** having three outputs Q_0 **211**, Q_1 **212** and Q_2 **213** respectively. The feedback is taken from outputs Q_0 and Q_2. The three least significant bits of the transmitter ID $\{i_2, i_1, i_0\}$ **201** are combined with the output of the pseudo random sequence generator $\{Q_2, Q_1, Q_0\}$ using EX-OR gates **208**, **207**, and **206**. The result can be used to indicate the frequency or frequency channel or frequency index $\{f_2, f_1, f_0\}$ **202** indicative of the frequency over

25   which the transmission will occur.

        Assuming that the initial state of the shift register is binary 111 (decimal 7; $Q_2=1$, $Q_1=1$ $Q_0=1$), the produced sequence is $\{7, 3, 5, 2, 1, 4, 6\}$. These numbers are then combined with the last three bits of the transmitter ID using bit by bit EX-OR operation; *i.e.* the last bit of the transmitter ID (i_0) is combined with the last bit of the random number (Q_0), etc. This way produced new sequence has numbers ranging from 0

30   to 7 the order of which depends on the last three bits of the transmitter ID. Thus, 8 distinct (permuted) sequences of numbers are created.

For example, if the last digits of the transmitter ID are 000, then the frequencies are selected in the order 7, 3, 5, 2, 1, 4, 6, *i.e.* the sequence is not altered. If the last three digits of the transmitter ID are 001, then the frequencies are selected in the order 6, 2, 4, 3, 0, 5, 7; if the last three digits of the transmitter ID are 010, then the frequencies are selected in the order 5, 1, 7, 0, 3, 6, 4; etc. Notice, that

5   each newly created sequence is not, strictly speaking, a permutation of the basic sequence because in each new sequence one number is converted to 0; *e.g.* in the first example 1 was converted to 0 in the process, in the second example 2 was converted to zero. However, for the purpose of this application the operation is regarded and called a "permuting operation" or a "permutation", or "permutation process", *etc.* Similarly, the resulting sequence is called "permuted sequence".

10   In the illustrative embodiment, the sequence length depends on the number of frequencies used by the system. For example, if the available bandwidth is 26 MHz and the frequencies are separated by a 100kHz interval, then there are 260 frequencies – channels available for transmission. *I.e.* the sequence length can be 255 by using an 8-bit shift register. By processing the output of the PN generator with 8 transmitter ID bits, a 255 different frequency sequences are obtained.

15   It is apparent that any two sequences are quite different even though the ID number is changed only on one position. In fact, the sequences are orthogonal, *i.e.*, for any two sequences, a coincidence of two numbers occurs only once for the entire period of the PN generator.

This is advantageous since it lowers the probability of persistent collisions that may happen if two or more transmitters transmit at the same time and at the same frequency for a prolonged time. It should be

20   stressed that using the sequences as described ensures that the persistent collision between any two transmitters is not possible since the frequencies in any arbitrary pair of sequences do not coincide persistently regardless of the relative shift of the sequences.

For each transmitter, the future frequency can be predicted based on just one partially received message because each message includes the transmitter ID based on which the receiver can determine the

25   content of the frequency index generator. To see how this can be done one needs to notice that the permutation process according to the illustrative embodiment is reversible: *i.e.*, if the same ID digits are applied again to the frequency index, the PN generator state is obtained. If the receiver receives a least a part of a message from a transmitter, the frequency index is known. It is only necessary to know the digits of the transmitter ID. The transmitter ID digits are included in the messages. Advantageously, they

30   are placed at the end of the message so that the receiver can recover them even if it starts the reception of the transmission in the middle of the message.

In some applications, this number of sequences my not be sufficient. For example, in many applications, the transmitter IDs are generated sequentially in the factory and embedded in the transmitter circuit. It would not be convenient or sometimes not even possible to make sure that all the transmitters to be installed on one premise or in geographical proximity would produce orthogonal sequences. In such cases the number of sequences can be extended to a larger number using other techniques, some of which were extensively studied and are described in the available literature. The number of available permutations of a sequence that has 127 numbers is 127! ($\approx$ 3E213). Even if a small subset of all the available permutations is used, the will be a large and adequate number of frequencies produced. This way, the manufacturer can still embed sequentially produced ID numbers and the transmitters could still be used without regard to the sequences that they produce. However, the method described above is advantageous for its simplicity and the unique properties or orthogonality of all sequences. The degree of orthogonality indicates how many hits (frequency agreements) there may be between two sequences upon any relative cyclic shift of the sequences. In a perfect design, for any two sequence that use the same set of frequencies, there would be only one hit. *I.e.*, if upon any cyclic shift of two sequences, a position is found in which the same frequency is present in both sequences, then the frequencies in all other positions would differ. The sequences produced in a manner as described in the advantageous embodiment are orthogonal in that sense. Although perfect orthogonality is not necessary for proper operation of the system, it is desirable since it reduces the probability of lost packets due to collisions. However, it should be apparent that other ways of permuting the sequences could be created. Another advantage of the advantageous method of permutation is that the permutation process is reversible as previously described. This property enables the receiver to synchronize based on the transmitter ID embedded in the transmitted messages without a need for additional information bits related to the PN generator status. Since the transmitter ID is normally required in the transmitted messages, the advantageous method does not require any overhead in the transmitted messages.

In order to preserve the property of orthogonality and zero overhead as described above and enlarge the number of transmitter ID universe the following advantageous method is employed.

Normally, the time intervals between transmissions are controlled by a quartz crystal and, ideally their nominal values are the same for all transmitters, however in the advantageous embodiment, the time intervals are perturbed by small time increments to further randomize the transmission events and lower the probability of persistent collisions with other transmitters as well as avoiding an intentional or unintentional pulsed interference. The transmitter control logic can accomplish this by programming the time interval

generator via line **27** (FIG. **1**) according to a predetermined algorithm. The information about the current status of the algorithm may be included in the transmitted packet to aid the receiver operation.

In the advantageous embodiment, the method of determining the time interval perturbation is based on a similar technique as described in conjunction with the frequency index generation, wherein the random sequence is used to alter the time interval between transmissions. *I.e.*, each time a transmission is performed, a new number is generated and used to determine the time interval between the current and the next transmission. Wherein, the time randomization is accomplished by processing the output of the PN generator used for the frequency index with bits of the transmitter ID. The processing is done as follows.

Referring to FIG. **4**, the frequency index is produced by the PN generator **203** outputs **213**, **212** and **211** and transmitter ID bits **201** – $\{i_2, i_1, i_0\}$ processed with EXOR gates **208**, **207**, and **206** to produce index digits **202** – $\{f_2, f_1, f_0\}$ as described previously in conjunction with FIG **3**. The PN generator output is further processed with transmitter ID digits **302** – $\{i_5, i_4, i_3\}$ by the AND gates **308**, **306** and **304** and by an EXOR gate **310**. The output of the gate **310** taken one bit at the time is a shifted replica of the output of the PN generator *e.g.* output **211** or **212** or **213**. Where the relative shift depends on the transmitter ID digits **302**. The output of the gate **310** is then fed to a shift register **312** whose outputs **323**, **322** and **321** are shifted replicas of the PN generator outputs **213**, **212**, and **211** respectively. When taken three digits at the time, the sequence produced at the output of the shift register is a shifted replica of the output of the PN generator. For example, if the PN sequence produced is order $\{7, 3, 5, 2, 1, 4, 6\}$, and bits i_5, i_4, i_3 are 011 then the shifted sequence is $\{4, 6, 7, 3, 5, 2, 1\}$; if the bits i_5, i_4, i_3 are 101 then the shifted sequence is $\{2, 1, 4, 6, 7, 3, 5\}$. This way, a total of 7 shifted sequences are produced (000 input is not allowed). The shifted sequences are further processed with bits i_8, i_7 and i_6 of the transmitter ID by EXOR gates **318**, **316**, and **316** to produce permutations of the shifted sequences at the outputs **333** – $\{t_2, t_1, t_0\}$ in a manner identical to the previously described in conjunction with frequency index generation. This way, each shifted sequence can be permuted in 8 different ways creating total 7*8=56 shifted-permuted sequences. The shifted and permuted sequences are used to produce variations of the time between consecutive transmissions. In the illustrative embodiment, the numbers from a sequence are multiplied by a $dT=2*Tm$ and added to the nominal time between transmission – TBT. Where, Tm is the nominal message transmission time. Advantageously, dT is rounded to the nearest discrete multiple of a basic time measure unit used by the control logic. If the permuted PN sequences are used as frequency indexes and the shifted-permuted sequences are used to randomize the time between transmission, then there are created 8*7*8 = 448 sequences that are time-frequency orthogonal in the sense that if two sequences coincide at one frequency and time, they will not coincide for any other frequency and time for the entire PN generator period. This is

based on merely 3-bit generator of the illustrative example! Of course, if a longer shift register is used for the PN generator, a far greater number of sequences are created. In the illustrative embodiment, an 8-bit generator is used as described previously. This results in over 16E6 orthogonal time-frequency sequences. Enough to relieve the manufacturer and applications from transmitter ID management other than sequential numbering of all manufactured transmitters. Of course, for a 8 bits shift register, 8 bits of the transmitter ID are used to obtain sequence permutation for frequency index, similarly, 8 bits are used for shifting and another 8 bits for permuting the shifted sequence to obtain the time delay variations.

The essence of this method is that in addition to two apparent dimensions of variability present in the form of permutations of frequency and time sequences, there is a third dimension added: *i.e.* the phase relationship variability between the frequency and time sequences. This rapidly increases a number of distinct orthogonal frequency-time sequences with increasing length of the basic PN generator as evidenced by the illustrative example. While it is possible to use other kinds of basic sequence and to use other ways of transforming the numbers of the basic sequence to obtain new sequences, the added new dimension has several advantages as evidenced in the illustrative embodiment.

The permutation process as described is an example of a more general process of transformation that transforms a set of numbers into another set of numbers (that may differ in size). It should be apparent that although a transformation resulting in the permutation as described is advantageous, other transformations may be used to derive frequency-time pattern based on the described principle.

It should also be apparent that in some implementations the order in which the shift and the second transformation (permutation) is performed may be reversed without altering the essence of the method.

Another advantage of the illustrative embodiment is that the permutations and shifting of the sequences can be performed by processing (transforming) one number of the sequence at the time, thus eliminating the need to store and manipulate the entire sequence. *I.e.*, the permuted or shifted sequence numbers are produced one at the time as needed based on numbers from the basic sequence that are also produced one at the time as needed.

Note, that this advantageous way of producing the frequencies does not require any overhead in the transmitted messages for the synchronization purpose other than the transmitter ID that is normally required any way. This is because the receiver can instantly recover the PN generator status based on just a single received message. As described previously, the receiver can infer the status of the 8-bit generator based on the received frequency index and the transmitter ID number. *I.e.* the message contains the

information about the 8-bit generator without explicit inclusion of the generator status bits in the message. In the illustrative embodiment, after the frequency index is obtained for a transmission, the time index is obtained by filling the shift register in the steps of storing the PN generator status, clocking the PN generator and shift register N times, and restoring PN generator status. This way, the content of the shift

5 register 312 is not required by the receiver to obtain synchronization because the time index depends on the future content of the PN generator that can be easily duplicated in the receiver based on the present content. Therefore, the receiver can still synchronize with a transmitter based on one received message and the message does not need to include any overhead for synchronization.

In an alternative implementation, a second PN generator synchronized with the first PN generator

10 may be used to produce the time variations wherein an information about the second generator phase is included in the transmitted message to aid the synchronization. Note, that synchronization of the first and the second generator in the transmitter is extremely important since the essence of the idea is that the cyclic shift of the second sequence is provided in respect to the reference provided by the phase of the first sequence. Only this way the resulting frequency-time hopping sequences produced in different

15 transmitters are distinct and orthogonal.

Although, the described implementation based on a single generator is advantageous since it results in a simpler implementation and lower overhead leading to a longer battery life, the two generator implementation can be modified to ensure low overhead as follows.

Both, first and second PN generators produce basic sequences whose length is 2^N-1 and 2^M-1,

20 wherein N and M are the lengths of the respective shift registers in both generators. In order to provide for synchronization between both sequences, each sequence is extended by one bit by inserting one "0" bit at a predetermined place in the sequence. The advantageous place is after N-1 or M-1 "0" bits in the respective sequences. This way the lengths become 2^N and 2^M respectively which ensures that both sequence lengths are related by a power of 2 (*i.e.* 2, 4, 8, etc.). Now, it is possible to ensure that both

25 sequences are always in the same phase relation; *e.g.* after initial reset which sets the generators in a predetermined state, both generators are advanced at the same time. This way, they will return to the exact initial state after the full period of the longer sequence. Of the particular interest is the case of the time generator producing a longer sequence than the frequency generator. In some applications, there is a limited number of frequency channels available, however there is still a need to produce a large number

30 of frequency-time orthogonal sequences. In such case, a longer time sequence can be used to expand the number of possible frequency-time sequences. For example if the frequency generator shift register has N bits and the time generator shift register has M bits, then the total number of sequences is $2^N * (2^M-1) * 2^M$

as shown in the preceding examples. Each time M is increased by one, the number of frequency-time sequences is enlarged approximately by a factor of four resulting in a rapid increase of the number of sequences with the increase of the time generator shift register length. Also, the synchronization requires a small overhead because the receiver can infer the frequency generator state and needs only the state of

5   the time generator. However, if the time generator is in precise phase lock with the frequency generator, the transmitter does not need to send the actual time generator state. Instead, the transmitter needs to include the information to remove the uncertainty created by the time sequence period being multiple of the frequency sequence period. E.g., if the time sequence is two times longer, the receiver needs to know if the time generator is in the first half or the second half of the sequence to determine the exact state of

10   the time generator. In this particular case, this information requires only one bit to be included in the transmitted messages. Of course, more bits are required if the time sequence is longer, e.g. if the time sequence is 4 times longer than the frequency sequence, two bits are required; for 8 times longer sequence 3 bits are needed, etc.

The described method (with one or two generators) produce a large number of time-frequency

15   orthogonal sequences in a simple and systematic way that enables the sequence selection by the transmitter ID and requires zero (or very small) overhead for synchronization. A system using a large number of time-frequency orthogonal sequences as described has an advantage of immunity to multipath fading, pulsed and frequency selective interference including intentional jamming, as well as low probability of self interference due to persistent collisions that may occur when two or more transmitters

20   transmit messages on the same frequency and at the same time for a prolonged period. A large number of produced frequencies enables the manufacturer and the system operators not to be concerned with the management of sequences for all the transmitters. Instead, each manufactured transmitter can produce a unique sequence that can be easily replicated in the receiver based just on the transmitter ID.

It is to be understood that the random frequency selection as described above and the time

25   perturbation can be used together or in separation to achieve immunity to collisions. I.e. (a) a fixed frequency pattern for all transmitters and random time perturbation patterns individual for each transmitter can be used, or (b) a fixed time interval between transmission or fixed time perturbation pattern and random frequency selection individual for each transmitter can be used, or (c) frequency and time changes can be combined to enhance the system performance at the expense of complication.

30   In the advantageous embodiment, both the transmission frequency and the time interval between transmissions are individually randomized for each transmitter by the transmitter ID bits.

It is also to be understood that one does not have to use the transmitter ID bits to individually predetermine the frequency and/or time patterns for each transmitter. In an alternative design, a random seed can be generated in the transmitter, for example just after reset, and used in lieu of the ID number to modify the frequency and time patterns. If the random seed has many bits, the probability of generating

5 the same pattern by two transmitters in the system is very small. However, this solution is considered inferior because it requires that additional steps are taken to associate the random seed number with the transmitter ID. In addition, this solution requires a good true random number generator that produces numbers with roughly the same probability in order to prevent frequent repetitions of some numbers. Also, although the probability of sequence repetition is small, it may be necessary to include an additional

10 step in the process installing the transmitter to reject a seed number that is already used by another transmitter. All this increases the complexity and the cost and potentially makes the installation more difficult.

It is also to be understood that the illustrated method and its components such as generators, registers, gates, *etc.*, can be realized in various forms of hardware some of which may include ASIC, or

15 software, or their combination.

Referring to FIG. 2, the receiver includes a reference frequency crystal oscillator 126 to produce a stable reference frequency on line 128 for the receiver circuits, a frequency selective radio receiver circuit 100 whose frequency is programmable via lines 116, to receive and demodulate a frequency modulated carrier when the frequency of the frequency selective receiver circuit is programmed according to the

20 frequency of the carrier, and a receiver control logic means 130 to process demodulated data, to provide system interface lines 140, responsive to the received data, and to program the frequency of the frequency selective receiver circuit. The control logic includes a receiver timer 132 establishing a time base to measure the elapsing time. The control logic also includes: (a) a plurality of ID memory registers 134 to hold digital data indicative of ID numbers for each transmitter that belongs to the system, (b) a plurality of time memory

25 registers 136 to hold digital data indicative of the time of the next transmission occurrence for each respective transmitter, and (c) a plurality of frequency memory registers 138 to hold digital data indicative of the frequency of the next transmission occurrence for each respective transmitter. In the advantageous embodiment, the registers are organized such that an arbitrary register *i* 151 of the plurality of ID memory registers 134 associated with a transmitter whose ID number is *n*, is associated with register *i* 152 of the

30 plurality of time memory registers 136 and register *i* 153 of plurality of frequency memory registers 138, wherein said registers 152 and 153 hold data associated with said transmitter *n*. The frequency selective radio receiver circuit 100 includes a RF band pass filter 104, an amplifier 106, an IF bandpass filter 110, a

mixer **108**, limiter-discriminator circuit **112** and frequency synthesizer **114**. The RF band-pass filter selects only the desired frequency band allocated for the transmission, the mixer mixes the incoming signal with the signal produced in the frequency synthesizer and produces an IF frequency (Intermediate Frequency). The IF frequency is filtered in a narrow band filter **110** whose bandwidth is selected according to the channel

5 bandwidth. The limiter discriminator demodulates the signal and produces baseband DATA signal **120** and an RSSI signal **118** indicative of the received signal strength. The DATA signal **120** and the RSSI signal **118** are converted to binary signals by A/D converters **124** and **122** respectively and fed to the control logic **130**. The presented architecture of the frequency selective radio receiver circuit **100** is known as a superheterodyne FM receiver, it is very well known and it does not require additional explanation. The

10 transmitted message data is extracted from the DATA signal **120** digitized by the A/D converter **124** using one of the many well-known methods for signal processing and does not require additional explanation.

In the advantageous embodiment, the frequency registers **138** hold for each transmitter the state of the PN generator used by the transmitter to produce the frequency indexes and time variations. If the synchronization is obtained with a given transmitter, the state of the PN generator is identical to that in the

15 transmitter. In the illustrative embodiment, the time registers **136** hold numbers - time of next transmission - for each transmitter representing the state of the receiver timer **132** at the time the next transmission is due from a transmitter.

In operation, the receiver control logic **130** sequentially compares the data content of the time registers **136** with the data content of the receiver timer **132** and if the transmission is due from a transmitter,

20 the control logic programs the frequency selective radio receiver circuit **100** according to the data content in the frequency register **138** for this transmitter, attempts to decode the demodulated signal, changes the content of the time register based on the number representative of the time interval between the transmissions for this transmitter and changes the content of the frequency register according to a predetermined algorithm for this transmitter. *I.e.* the frequency and the time registers are updated each time

25 a transmission is due regardless whether the packet was received successfully. The new content of the frequency register is determined according to the algorithm for the frequency use by the transmitters.

The new content of the time register is calculated based on the current content of the receiver timer and a number representative of the time between the current transmission and the next transmission for this transmitter, wherein said number is calculated based on the nominal value of the time between the

30 transmissions and adjusted by the pseudo random perturbation performed according to the previously described algorithm. In addition, said number is corrected by a correction factor based on the measured difference between the transmitter time base and the time base of the receiver, wherein said difference is

determined in a manner described later in details. In the advantageous embodiment, the numbers representative of the time base differences are stored in the time registers **136** separately for each transmitter and are independent from the numbers representing the time of the next transmission, *i.e.* the time registers are split to hold two independent numbers.

It should be noted that even if crystal oscillators are used in the transmitters and the receiver to control the timing, the error accumulated during the time between transmissions can be significant compared to the packet time. For example, if the nominal period between the transmissions is 100 seconds and the crystal frequency error due to tolerance and temperature changes is +/- 20 ppm (parts per million) for the transmitter and +/- 10ppm for the receiver, then the error may be as large as 3ms. If the time for the transmission of one packet is 5ms, then the error is significant. In reality, such tight tolerance is difficult to achieve and expensive and therefore in many applications a much bigger error will be accumulated. In order to minimize the time error accumulated during the long time between the transmissions, the receiver can store the time difference between the ideal and the actual time of the packet reception and use the difference to predict more accurately the next transmission time. For example, if the timer resolution is 0.25ms, then the next transmission time can be predicted with accuracy 0.25ms, providing that the temperature does not change appreciably over 100s period. This represents an improvement of an order of magnitude. *I.e.* the receiver can program its frequency 0.25 ms in advance to each new frequency, examine it for the duration of the packet, then program to the next frequency and so on.

During the acquisition, when the time error is not known, the receiver needs to tune to the first frequency at least 3 ms in advance. Then, the receiver monitors the received signal by observing the RSSI signal **118** and DATA signal **120**. If during the next 6 ms no valid signal is present, the receiver programs to the next frequency 3 ms in advance and so on. Of course, if worse tolerances are used, the time the receiver dwells on a single frequency expecting the next transmission is proportionately longer.

Some embodiments of the present invention relates to the reading of electric utility meters. In such embodiments, the transmitters advantageously use the power-line as a frequency reference from which the time intervals between transmissions are derived. The advantage of this arrangement is that all transmitters time drifts in the same proportions relative to the receiver. This can ease the receiver task of acquisition as well as tracking.

However, in the illustrative embodiment, to ease this acquisition problem, the receiver includes a frequency error detection means and a method as described below.

In the advantageous embodiment, the receiver includes a frequency error detection means **142** that is advantageously implemented as a simple digital counter, in order to detect the frequency error in the received signal in respect to the receiver reference frequency by measuring the frequency error of the intermediate frequency signal **111**. In addition, in the transmitter, the transmitted carrier frequency and the time interval generator timing are derived from the same source and in the receiver, the receiver frequency and the receiver timer are derived from the same reference. In operation, the receiver can measure the frequency difference between the transmitted carrier and the receiver frequency and use the measured error to determine the difference between the transmitter reference frequency and the receiver reference frequency based on just one partially decoded message. The frequency difference measurement is accomplished in the following way. Assuming that the transmitter frequency accuracy is +/-20ppm and the receiver is +/-10ppm, the carrier frequency is 915MHz and the IF frequency is 10.7MHz, the absolute maximum error between the receiver frequency synthesizer and the received carrier can be as much as 2760Hz (915E6*20E-6 + 925.7E6*10E-6). *I.e.*, the resulting IF frequency is offset from its nominal value by this amount. This represents 260ppm of the nominal IF frequency. An ordinary frequency counter with a time base accuracy determined by the receiver crystal oscillator, *i.e.* +/-10ppm can detect this error and measure it with good accuracy. The accuracy should be better than +/-110Hz (1/26 of the maximum error). Based on the measured frequency error, the relative frequency offset is calculated and the time correction factor for each transmitter is adjusted accordingly. For example, if the measured error is +1380Hz then the relative frequency error is approximately equal to +15ppm. If the nominal value of the time interval between two consecutive transmissions is 100 seconds, then the required correction is +1.5 ms if the receiver uses high injection, *i.e.* the frequency of the synthesizer in the receiver is nominally equal to the received frequency plus the IF frequency, and -1.5ms if low injection is used.

In the advantageous embodiment, the time base correction factor stored for each transmitter is also used to adjust the center frequency of the receiver and thus aid the reception of the transmitted packets, thus lowering the requirements for the length of the preamble included in each packet for the purpose of carrier and data timing acquisition. This is accomplished by adjusting the receiver frequency momentarily just prior to the reception of the packet from a transmitter from which a packet is due.

In the advantageous embodiment, when a transmitter is powered up, for example after a battery replacement, it enters a power-up mode during which a predetermined number of packets are transmitted on a number of selected frequencies. In the power-up transmission sequence, each packet includes a number that indicates how many packets the transmitter has transmitted in this mode or how many packets the transmitter will transmit in this mode before entering a normal mode of operation. This way,

the receiver can synchronize with the transmitter just after a single packet reception by calculating when the first transmission will occur in the normal mode.

In operation, the receiver scans the selected frequencies during the time when it is not occupied with the scheduled reception from the transmitters or checking the time registers. Also the receiver scans all the available frequencies in addition to the selected frequencies. During the scan, the receiver uses RSSI signal to detect if there is an energy transmitted on a current frequency; if so, then the receiver measures a predetermined unique properties of the modulated carrier. If the energy is not present or the unique property is not valid, the receiver will quickly proceed to examine the next frequency. Otherwise the receiver will stay on this frequency and try to decode the message. This way all the selected frequencies are examined several times per second ensuring that the receiver can receive a power-up message. Also, the scan of all available frequencies is fast; the synchronization can be regained faster and more reliably because the receiver will not waste much of the time for an examination of very weak or spurious signals.

In the advantageous embodiment, the transmitter ID numbers for each transmitter stored in the receiver ID memory registers **134** are acquired and stored by the receiver during a process of log-in. Each new transmitter to be logged-in is placed in a relatively close proximity to the receiver and then powered up. A very high level of the received signal ensures that the new transmitter signal is not mistaken for another transmitter. A successful log-in is confirmed by the receiver using an audio or a visual indicator that can be included in the receiver or in the system controller connected to the receiver via system interface **140**. The receiver may reject the transmitters that can cause persistent collisions, *i.e.* if its ID number has the last 24 digits identical to another transmitter already present in the system.

One of the fundamental concerns in some types of such systems is the need for transmission of urgent messages. Such a need arises in *e.g.* security alarm systems. In such systems, the regular transmissions occur at relatively long time intervals in order of 100 to 200 seconds or even more. According to the description given earlier in this application, these transmissions can occur at constant or varying time intervals. They are referred to as "routine" transmissions. Typically, they merely carry status information indicating that the transmitter is operative and may include some additional information, *e.g.* battery status. Therefore, these "routine" transmissions are also referred to as "status" transmissions. It may be convenient to think of them as "scheduled" transmissions.

Another example of such a system is a heating and air-conditioning system. In such a system, there may be several "thermostats", each including a frequency hopping transmitter. Each thermostat

urgent transmissions because the transmission opportunities are rarely used by the urgent transmissions as opposed to the routine transmissions that typically always occur at their "opportunities".

For illustration, consider FIG **6b**.

In all the following figures, for illustration purpose, the transmissions are marked as boxes with continuous line, and the transmission opportunities in which the transmissions do not occur are shown as boxes with broken lines.

The transmission opportunities are shown in each of the time intervals: **605, 606, 607** in interval T_i , **609, 610, 611** in interval T_{i+1} , **613, 614, 615** in interval T_{i+2} , *etc*. They are depicted as indexed time slots. The indexes are indicative of the frequency (or frequencies to be used). It should be noted that although there are only three opportunities shown, in reality there may be hundreds of them in a single interval. For example, if the interval has 200 seconds and the opportunities are every 250ms, then there are 800 opportunities in this time interval. In the illustrative example, the indexes are assigned according to a very simple rule: for each opportunity, the index is incremented by one starting from the last status transmission, and reset at the end of the interval back to the value of the last status transmission. Then, the index is incremented by one for the next status transmission and the entire process is repeated, *etc. I.e.* the opportunities following status transmission with index *i*, have the frequency index *i+1* (**605**), *i+2* (**606**), *i+3* (**607**), the opportunities following status transmission with index *i+1*, have the frequency index *i+2* (**609**), *i+3* (**610**), *i+4* (**611**), *etc.* The status transmissions **604, 608, 612, 616** have indexes *i, i+1, i+2, i+3*, respectively, exactly as in FIG **6a**.

This way, the status transmissions are transmitted with indexes that are incremented by one for each consecutive transmission, and the indexes for each opportunity are easily referenced to the last transmission. There is no particular significance to this assignment, and many other assignments are possible, some of which are highlighted later. In the illustration, the opportunities are separated by interval Ts **619**, that is shown to be equal for each pair of opportunities. In advantageous implementation, these intervals can be varied in a similar fashion as previously described in conjunction with frequency and time hopping. Of course, a different advantageous indexing may be used to obtain orthogonality of frequncy-time sequences for each transmitter. This has been described in details earlier and does not need additional explanation.

FIG **6c** illustrates what happens when an alarm event occurs. Assuming that an alarm event **618** happened to occur some time after opportunity **609** but before opportunity **610**, it is shown that the alarm transmission are performed at opportunities **610, 611, 613**, and **614** following the alarm event.

Optionally, the alarm message may also be transmitted at the slot **612** at time and frequency scheduled for status message or the status transmission may include an alarm indicator. The alarm transmissions are performed for a known duration Ta **620** or until a known number of transmissions is performed. This simple way of indexing the status and alarm transmissions is advantageous for its simplicity and for

5   consistent indexing of the status transmissions regardless whether the alarm transmissions are performed.

FIG **6d** illustrates another simple way of indexing. In this case, the indexes are assigned in such way that they are used consecutively for each transmission including status and alarm transmissions. This is advantageous for frequency usage to be evenly distributed over all frequencies, but requires more careful receiver operation since it is easier to lose synchronization with the status transmission sequence.

10.   Of course, in both examples, the actual values of indexes depend on when the alarm event **618** occurs and on the duration or equivalently the number of transmissions in the time slots following the alarm event.

It should be apparent, that there can be many different ways of establishing the time slots and many different ways of assigning frequency index to each slot. One can, for example, use a special

15   sequence that always starts alarm transmissions from the same index, or the special sequence may run continuously advancing for each opportunity, one might reference the slot time to the last transmitted message or to another time reference related to many previous and even future transmissions, one may synchronize the special sequence to the status sequence or one may convey the alarm sequence status in the status transmissions, *etc., etc.*

20   One interesting example is described below for illustrative purpose. According to this implementation, one can create a continuous sequence of indexed time slots and "decimate" them for the purpose of transmitting the status transmission, *i.e.* skip over without transmission in most of the slots. Then, when alarm occurs, transmit the alarm messages more often (using different decimation factor, or not decimating at all, *i.e.* transmitting more often). Advantageously, the decimation factor can be used

25   that is **L+1**, where **L** is the sequence length. For example, if the sequence numbers are **0,1,2,3**, *etc.*, the indexes used for the status transmissions will be in the same order **0,1,2,3**, *etc.* This is illustrated in FIG **6e**. There, the sequence length is 3 and the numbers are is 0,1,2; the decimation factor is 4. This is a very elegant way to look at the idea and event to implement it. Of course, the decimation will work just as fine with any factor that is $n*L+1$, where n is a natural number.

30   In FIG **6f**, another implementation is illustrated, using two intertwined sequences that are different from each other; first used for scheduled (status) transmissions and the second used for alarm transmissions. As mentioned before, they can be precisely synchronized with each other, so that the

sends "routine" transmissions, at intervals, including temperature reading data, to a receiver controlling the heating and air-conditioning system.

Referring to FIG. **6a**, the status transmissions are transmitted at time intervals T_i **601**, T_{i+1} **602**, T_{i+2} **603**, etc. In the figure, they are shown to be equal although they do not have to be. Each status transmission is shown to occurs at the beginning of each time interval, although this is, of course, arbitrary. The transmissions and intervals are indexed for reference. Accordingly, the transmission **604** having index i is followed by transmission **608** having index $i+1$ and which in turn is followed by transmission **612** having index $i+2$ etc. As indicated before, each transmission can use one or more frequencies at the same time or one at the time. The time intervals may also be varied advantageously as previously described. The indexes are also used to determine the frequency (or frequencies) for the transmission and, in another advantageous implementation, the duration of the interval between transmissions. Advantageously, as indicated before, these determinations may be done individually for each transmitter. For the illustration of the basic idea, let's assume that the time intervals are fixed, and that the indexes indicate the frequency used for the transmission.

When an urgency occurs, e.g. an alarm condition, an urgent message must be transmitted to the receiver promptly; waiting 200 seconds or even 10 seconds for the next scheduled time for the next transmission is not practical. In general, such a message is referred to as an "urgent message" and a transmission that carry such message is called an "urgent transmission." It may be convenient to think of such messages as "unscheduled", although, as is shown later, this is not a precise description. Suppose that the alarm occurs in the middle of the interval **602**. It is evident, that in order to transmit the alarm message during the next scheduled transmission, the transmitter needs to wait for several tens of seconds.

Note, that the distinction between the message and the transmission is made to indicate that they may not be the same. E.g. one transmission may convey only a fraction of a message or more than one message.

Similarly, in a heating and air-conditioning system, when a user adjusts the temperature on a thermostat, he expects almost immediate action, e.g. the furnace fires-up or the air-conditioner turns on. This requires that the transmitter sends an "urgent" message to the receiver much in the same fashion as in the alarm systems.

In a frequency hopping system according to this application, the fundamental problem is that the receiver tracks time and frequency for all the scheduled transmissions, but without knowing when and where to expect the alarm message, it has difficulties to receive such transmission. It does not help to know what the next frequency may be without knowing the time because this frequency may be not

usable, for example due to multipath fading. It is therefore necessary that the transmitter transmits at more than one frequency. *I.e.* change the transmission frequency, perhaps even several times. However, a change has to occur at some time. If that time is unknown, the receiver cannot follow to the new frequency. This is a difficult problem.

5   In one possible solution, the transmitter repeats transmission of the alarm transmissions at many frequencies for a predetermined duration or a predetermined number of times. The receiver scans all the frequencies all the time to find out if there are any such transmissions, in hope that it will eventually stumble on one of such transmissions. The interception of such transmission is probabilistic, *i.e.* a matter of chance. In many cases, this is problematic. Consider the following example. Assume that the

10   message time is 5ms, that there are 128 frequencies, and that receiver needs 1ms to scan one frequency to determine if a message is being transmitted.

      In this example, the probability that a single message is intercepted, at least in part, is 5/128, *i.e.* very small. Many transmissions are needed to make this probability acceptably high. For example, if a 100 messages are transmitted, the probability that all are missed is still very high – approximately 20%.

15   Almost 300 messages are needed to make the probability less that one in a million.

      This solution has several drawbacks, one of them is excessive battery drain, especially if the alarm events occur frequently. For example, in a door monitoring transmitter, were each closing or opening the door activates the transmitter.

      In an alternative implementation, to increase the probability of a single transmission interception,

20   the alarm messages may be transmitted at a smaller number of specially assigned alarm frequencies. For example, if 8 frequencies are used then 15 transmissions are sufficient to achieve less than one in a million probability that all the transmissions are missed.

      However, this method also has drawbacks; for example: the assigned frequencies are easy to interfere with by an intentional jammer, the immunity to impairments such as multipath and interference

25   is reduced, there may be regulatory limitations that may not allow transmission of excessive energy on selected frequencies, *etc.*

      Accordingly, the new method described here solves all these problems and provides a solution to the fundamental problem without apparent drawbacks with ease and elegance.

      The following is a description of an illustrative example of an implementation of the new method.

30   For the purpose of transmission of urgent messages that need to transmitted before the next status transmission, there are established multiple transmission opportunities at certain times. These opportunities are established in each time interval between status transmissions. When such opportunity

has a frequency index assigned to it based on which a transmission frequency is assigned to this opportunity, the transmission opportunity becomes more than simply a time slot. The transmission opportunities, then, have two coordinates: time and frequency. They are referred to as "transmission opportunities" having "opportunity time slots" and "opportunity frequency index". It should be also

5 obvious that in some applications, advantageously, a spreading code can be used, *e.g.* as in direct sequence spread spectrum, or multicarrier spreading. In such a case, it can be said that an additional coordinate is introduced, that is the spreading code.

For the purpose of this specification, the term "transmission opportunity" is defined as: (i) time, or (ii) frequency, or (iii) code, or (iv) any combination of (i), (ii), and (iii) at which a transmission might

10 occur.

Advantageously, the opportunity time slots are at relatively much shorter time intervals, *e.g.* 250ms compared to the status transmissions that are at intervals of 100-200 seconds.

In operation, the receiver checks each opportunity for transmission by tuning to the right frequency at the right time. Normally, the transmitter is not concerned with the time slots and the

15 transmission opportunities. It simply transmits the status messages when due. Consequently, normally, there are no transmissions transmitted at these opportunities. However, when an alarm condition occurs, the transmitter computes the time and the frequency index of the next transmission opportunity. Then, the transmitter transmits the urgent message at the next transmission opportunity, *i.e.* at the right time and frequency. This transmission can be repeated at several transmission opportunities to improve reliability.

20 Of course, in both, the receiver and the transmitter, the time and frequency index of the next opportunity are computed based on some convenient reference, *e.g.* the time and frequency of the last status transmission. Obviously, the computation is done according to an algorithm that is consistent for both the transmitter and the receiver.

It should be apparent, that as long as the receiver maintains synchronization with the status

25 transmissions, it is able to receive every transmission at every opportunity providing that the transmitted signal is not impaired by fading of interference. This is a vast improvement.

In another implementation, advantageously, the routine transmissions are transmitted at some of the transmission opportunities, which makes it convenient for the receiver to maintain synchronization and to compute the time and frequency for the future transmission opportunities.

30 For convenience, similarly, one can think of the frequency and time coordinates for the routine transmissions as "routine transmission opportunities", although this is not the same as in the case of

receiver can reproduce the second knowing the phase of the first. Alternatively, the phase information of the second sequence may be included in the status transmissions.

All these variations are possible within the scope of the described idea. One needs to recognize that these implementations are mostly a mechanical variation of the basic idea as described.

5   The essence of the idea is that, firstly, the transmission opportunities for urgent transmissions do exist at precise times and, secondly, that each opportunity for transmission has a precise frequency index (and possibly a spreading code) assigned, which allows the receiver to compute the expected transmission time and frequency and to tune to specific frequencies and only at precise times when the alarm transmissions *can* be transmitted. Furthermore, advantageously, the transmission opportunities are

10 developed in relation to the routine transmissions, that in effect provide synchronization for the transmission opportunities. In other words, the urgent transmissions can only occur at certain discrete coordinates that, advantageously, can be related to the routine transmissions.

This method has several advantages. One advantage is that each alarm transmission reception is no longer probabilistic. *I.e.* each transmission can be received (providing that the propagation conditions and interference level permits it). Consequently, the necessary number of transmissions is just one,

15 although more than one can transmission may be utilized in order to compensate for impairments due to propagation and interference. Obviously, this saves battery and reduces interference created by multiple transmissions. Another advantage is that it is more difficult to intercept and jam the alarm transmissions. Yet another advantage is that the receiver uses only a fraction of its time to track one transmitter. For

20 example, if the slots are established on average every 250ms, and the receiver needs 1ms to check if a transmission is being performed, then the receiver needs to spend only 4ms in one second for one transmitter. This is equivalent to 0.4% of the time. Also, the response is almost instantaneous. The sub-second delay is inconsequential in most practical applications.

25 The transmission opportunities can also be used for the purpose of power-up synchronization. On power-up, a transmitter transmits "power-up transmissions" referred to as "synchronization transmissions". As described before, the receiver scans all the frequencies including selected frequencies (if present,) and can detect pending transmissions with a rather low probability. The number of transmissions can be set to be very large so that the probability of losing all of them is arbitrary small.

30 When at least one transmission is received, the receiver can synchronize using the method described earlier. Then, the receiver can track the time and frequency of the subsequent transmissions from this transmitter.

When the power-up transmissions end, the transmitter enters normal mode of operation in which it transmits the status messages at long intervals. The receiver must somehow recognize this moment of transition and start tracking the time and frequency of the status transmissions. There is a difficulty, though. Since one or more successive transmissions can be lost because of fading and interference, the

5   receiver can not be sure when the power-up transmission has ended. To remedy this situation and eliminate the uncertainty, the following method is used. The precise moment at which the transmitter makes the transition is precisely defined. The transition is defined in such way that the receiver can compute the time in which the transition will occur based on just one correctly received transmission from the transmitter.

10   In one implementation, in order to convey the moment of transition to the receiver, the transmitter includes a status of counter in the transmissions. The counter is decremented once per each transmission. The transition occurs when the counter reaches zero.

In an alternative implementation, the moment of the transition is defined to be a particular state of the generator used for the frequency pattern. As shown earlier, it is not necessary to include explicitly the

15   generator status in the transmissions in order to obtain synchronization. Instead, if the frequency pattern is based on processing the transmitter ID with the state of the generator, the transmitter ID alone is sufficient. The ID, then, indicates the generator state implicitly. This state, when recovered based on the detected message, can be used to obtain the precise moment of transition.

It should be apparent that both methods are similar in that they both require that certain indicium of the future time of transition is included in the transmissions. Equivalently, the indicium may be

20   indicate a time and a frequency of at least one future routine transmission. In another implementation the indicium can indicate an urgent transmission opportunity. In this case, the receiver first tracks the transmission opportunities and then tracks the routine transmissions in two step synchronization process.

The further step in improving the power-up synchronization method is to transmit the power-up

25   transmissions in the transmission opportunities as defined earlier. In such case the transmissions occur at each transmission opportunity and the separation time between two opportunities is set to be rather small, e.g. 25ms. This way, the time needed for the transmission of a certain number of transmissions can be precisely and easily computed, since it does not depend on the transmission duration and certain latencies that may occur in the transmitter processor when transmitting multiple transmissions one after another.

30   An additional advantage is that the receiver can more readily attempt tracking of the synchronization transmissions. For example, in many cases the receiver receives just a partial

transmission and is not able to recover most of the data in the transmission. The receiver, then, can examine one or more "suspected" transmission opportunities. These suspected opportunities can be determined based on the received transmission time and frequency. In order to facilitate this better, all the transmitters may use the same frequency hopping pattern during synchronization transmissions. This

5   way, the receiver can compute easily the next frequency and time.

In another implementation, each transmitter may use individual frequency-time hopping pattern. The receiver then can compute the next "hypothetical" transmission opportunity for each transmitter whose ID is entered into the receiver memory. As explained earlier, this can be done by recovering the pattern generator state using the present frequency and the transmitter ID. Subsequently, the receiver can

10   then examine all or almost all next opportunities for all possible transmitters. Since the transmissions are individually time hoped, the computed opportunities will not coincide. Using the transmission opportunities for the transmissions will also give the receiver time to process the received messages and to tune to the new frequencies.

In any case, many transmissions are performed per second which ensures a rapid receiver

15   synchronization. This is important since the installation and battery replacement procedure typically requires a prompt indication that the transmitter is operating properly.

The synchronization transmissions can be performed when the transmitter is activated in a specific way to prompt such transmissions. Such activation may be in a many different forms, *e.g.* a reset on power-up, pressing a switch, electrical signals at the interface input, *etc.*

20   The described methods are illustrated in FIG. **7a** and **7b**.

In FIG **7a**, the transmissions **701, 702, 703** and **704** are the synchronization transmissions, and the transmissions **705, 706** are the first routine transmissions following the synchronization transmissions. The synchronization transmissions are based on the internal states of the frequency pattern generator as described previously. These states are now numbered here for convenience. Thus, we have the

25   transmission **701** based on the state number **L-3**, the transmission **702** based on the sate **L-2**, *etc.* When the last state **L-1** is reached, the generator "wraps around" and starts anew beginning with a state number **1**. This transmission can be also considered to be the first routine transmission. The next routine transmission time and frequency is based on the state number **2** and is computed accordingly. The synchronization transmissions are separated by time **707**, and the routine transmissions by time **708** and

30   **709**.

In FIG **7b**, the transmissions for two transmitters are shown, to illustrate the case of individual frequency-time hopping in during the synchronization transmissions. There are shown two synchronization transmission sequences from two transmitters, with IDs of **#Q** and **#P**. The transmitter **#Q** transmits the sequence that includes the synchronization transmissions **716**, **717**, **718**, and **719**, and

5   the routine transmission **720**. The transmitter **#P** transmits the sequence including transmissions **710**, **711**, **712** and **713**, and the routine transmissions **714** and **715**. The synchronization transmissions of the transmitter **#Q** are separated by individually varied time: **724** and **725**. The routine transmissions are separated by individually varied time **723**. Similarly, for the transmitter **#P**, the synchronization transmissions are separated by individually varied time **726** and the routine transmission are separated by

10   individually varied time **721** and **722**. To see the intricacy of this approach consider the transmission **712** and **716**. Suppose that the receiver during scanning of all channels received an incomplete transmission at certain time and frequency. Then, the receiver can make an assumption that this transmission comes form either transmitter **#Q** or from the transmitter number **#P**. Then the receiver recovers the generator state for both transmitters as described previously. Based on the recovered states, the receiver can

15   compute the next transmission time and frequency for both transmitters. If the transmitters use the described method of frequency and time hopping, the sequences are orthogonal. That means that the next transmission time-frequency will be different for both transmitters. If the transmissions do not coincide in time, the receiver can examine both transmissions by tuning to the right frequency at right time one at the time. If they coincide in time, they do not coincide in frequency, in which case the receiver can

20   examine one transmission for the first transmitter. Then, the receiver can compute the next transmission time and frequency for the second transmitter and proceed to examine the following next transmission from the second transmitter. This transmission may still occur at the same time as the second transmission from the first transmitter, but it will be at different frequency. Therefore the receiver will have no trouble with alternating between two transmitters and receiving the transmission from both of

25   them.

Of course, this method can be extended into a scenario including many transmitters.

In this method, by relating the synchronization transmissions with the transmission opportunities that are related with the routine transmissions, the concept of opportunities as described earlier is extended back in time.

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